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High spatial resolution observations of CUDSS14A: a Scuba-selected Ultraluminous galaxy at high redshift

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ABSTRACT

We present a high-resolution millimetre interferometric image of the brightest SCUBA-selected galaxy from the Canada-UK deep SCUBA survey (CUDSS). We make a very clear detection at 1.3 mm, but fail to resolve any structure in the source. The interferometric position is within 1.5 arcsec of the SCUBA 850 μm centroid, and also within 1.5 arcsec of a 44 μJy radio source and a very faint, extremely red galaxy which we had previously identified as the submillimetre source. We also present new optical and infrared imaging, and infrared spectroscopy of this source. We model the overall spectral energy distribution and conclude that it lies within the redshift range $2 < z < 4.5$. The submm/FIR luminosity of CUDSS14A is very weakly dependent on redshift within the constrained range, and is roughly 4×10^{12} $L_{\odot}$ (for H_0=75 and an assumed Arp220-like spectrum), which implies a star-formation rate $\sim$1000 $M_{\odot}$ yr^{-1}. We derive an approximate gas mass of $\sim 10^{10}$ $M_{\odot}$ which would imply the current star-forming activity cannot be sustained for longer than about 10 million years. With the present data however we are unable to rule out a significant AGN contribution to the total luminosity.

Key words: Galaxies, SCUBA sources, galaxies, high-redshift

1 INTRODUCTION

The commissioning of SCUBA on the JCMT has revolutionized the field of observational cosmology and in particular the study of galaxy evolution, arguably making as big an impact as the release of the Hubble Deep Field did a few years earlier.

Something of the order of 50 galaxies have now been discovered in the various deep SCUBA surveys (Smail et al 1997, Hughes et al 1998 , Barger et al 1998, Eales et al 1999) and at least 30 percent of the far-infrared/submillimetre background discovered by COBE (Puget et al 1996, Fixsen et al 1998) has been resolved. Considerable effort is now being dedicated at ground-based telescopes in the radio, infrared and optical, as well as Satellite observatories such as the Hubble Space Telescope,XMM-Newton and Chandra, to following up these sources, making identifications and obtaining redshifts, so that the history of star-formation in the Universe can be properly characterised free of the obscuring effect of dust.

Accurate positions are of course essential for identifications and follow-up observations, and the 15 arcsec SCUBA beam at 850 μm allows an uncertainty of several arcseconds even on a high signal-to-noise detection. Deep VLA imaging has been quite successful at providing identifications and accurate positions of a number of SCUBA-selected sources (Smail et al 2000, Richards 1999). However, $\leq 50\%$ of SCUBA sources are detected with the VLA, even at $\sim 10\mu$Jy sensitivity levels, and in some cases even with a VLA detection there may be some ambiguity in the identification (Richards 1999, Downes et al 1999). The only way to truly *confirm* the identification is to make a higher resolution millimetre or submillimetre image using an interferometric array (Frayer et al 1998,1999,2000; Downes et al 1999).

In this paper we present the results of an observation with the IRAM interferometer on Plateau du Bure of CUDSS14A, the brightest source discovered in the CUDSS as reported by Eales et al (1999), along with new high resolution J and K images obtained with the CFHT Adaptive Optics system PUEO which we combine with archive HST images at 606 and 814 nm (roughly V and I), and also new

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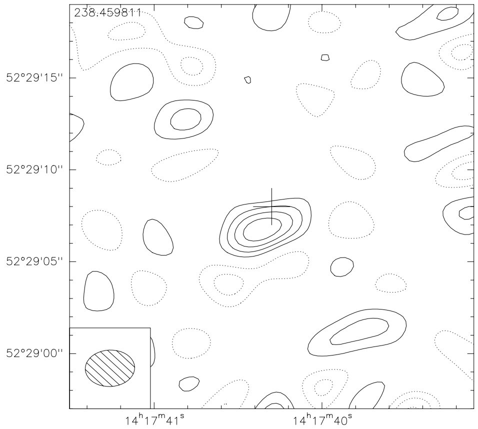

Figure 1. The 1.3 mm map of CUDSS14A, contours are in steps of 0.5 mJy, the 1 sigma uncertainty, and extend from -2 $\sigma$to $+5\sigma$.The cross marks the nominal SCUBA position on which the observation was centred. The effective beam shown is 2.7 × 2.0 arcseconds with the major axis at a PA of 93 degrees.

infrared spectroscopy obtained on the United Kingdom Infrared Telescope (UKIRT).

2 OBSERVATIONS

2.1 IRAM Observations

The IRAM data were taken on 25, 26 and 28 November 1998. The array was in the 5D configuration, and the source was tracked for 8.4, 3.3 and 10.6 hours on each night respectively. Flux calibration was performed against CRL618, 3C273 and MWC349 with 1637+574 and 1418+546 being used as phase calibrators. The observations were centred on the nominal SCUBA position of (J2000) 14 17 40.3 +52 29 08 and observations were made at 1.3 mm (238.5 GHz) and 2.8 mm (105 GHz) simultaneously. The data were correlated and reduced at the IRAM headquarters in Grenoble using the standard software.

The 1.3 mm map is shown in Figure 1 (we note that Bertoldi et al 2000 have produced an essentially identical map from the same data). The object is very clearly detected at a level of 6 σ, and the positional centroid is 14 17 40.37 +52 29 06.8, or 0.6 arcsec in RA and 1.2 arcsec in declination away from the nominal SCUBA position. We estimate the total uncertainty of the IRAM position to be $\pm$ 0.3 arcsec (see Downes et al 1999 for a detailed discussion of the different factors affecting the positional uncertainty of IRAM interferometer maps). There is no evidence for any extension beyond the beam. We also examined the data for any evidence of spectral line emission but found none, however this does not place any meaningful limits on the redshift.

There was no detection at 2.8 mm. The 1.3 mm flux and 2.8 mm upper limit are shown in Table 1, along with the SCUBA and ISO measurements. The overall flux distribution, which is very similar to other SCUBA-selected galaxies (e.g. Ivison et al 1999), is plotted in Figure 2.

Table 1. Radio, Submm and ISO photometry

Wavelength	Flux (mJy)	reference
6 cm	0.044 $\pm$0.004	Fomalont et al.1991
2.8 mm	3σ <0.54	this paper
1.3 mm	2.94 $\pm$0.49	this paper
850 μm	8.8 $\pm$1.1	Eales et al 1999
450 μm	3σ <31	Eales et al 1999
15 μm	3σ < 0.2	Flores et al 1998a
7 μm	3σ < 0.15	Flores et al 1998b

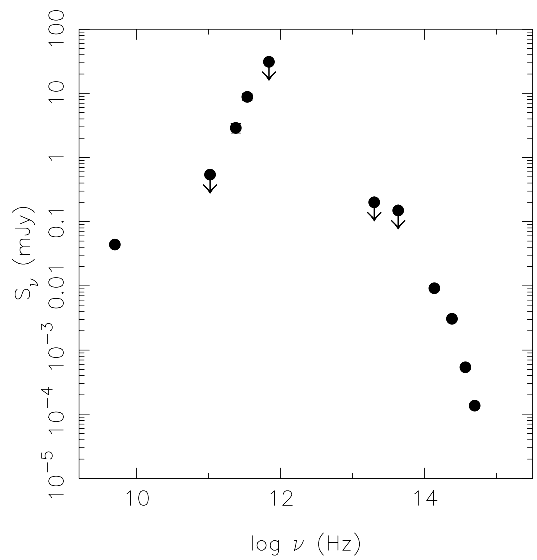

Figure 2. The overall radio through optical observed flux distribution of CUDSS14A.

2.2 New CFHT Observations

Observations were made with the PUEO Adative Optics system on CFHT during the nights of April 27-28 1999, using an R=15.3 guide star 26 arcsec WNW of the target. The detector was a 1024^2 HgCdTe array sampling the image at 0.035 arcsec/pixel. Secure detections were obtained in a total of 150 minutes integration in J and 100 in K'.

The new infrared images have been co-registered with archival HST images in F606W and F814W (the source is in the so-called 'Westphal' survey field), resampling to a pixel scale of 0.1 arcsec/pixel. A montage of the F606W, F814W, J and K' images is shown in Figure 3. The morphology of the source appears compact and indistinct. The FWHM of the images are about 0.4 arcsec in all of the bands, substantially larger than the PSF in the HST data. The PSF is poorly constrained in the Adaptive Optics images but is most likely substantially smaller than 0.4 arcsec.

Table 2. Multi-aperture optical/infrared photometry (AB mags)

Filter	1 arcsec	2 arcsec	4 arcsec
F606W(HST)	27.132±0.314	27.011±0.351	26.063±0.263
F814W(HST)	25.228±0.127	25.023±0.128	24.574±0.128
J(CFHT)	23.230±0.094	22.866±0.124	22.686±0.215
K'(CFHT)	21.423±0.047	21.195±0.072	21.495±0.197

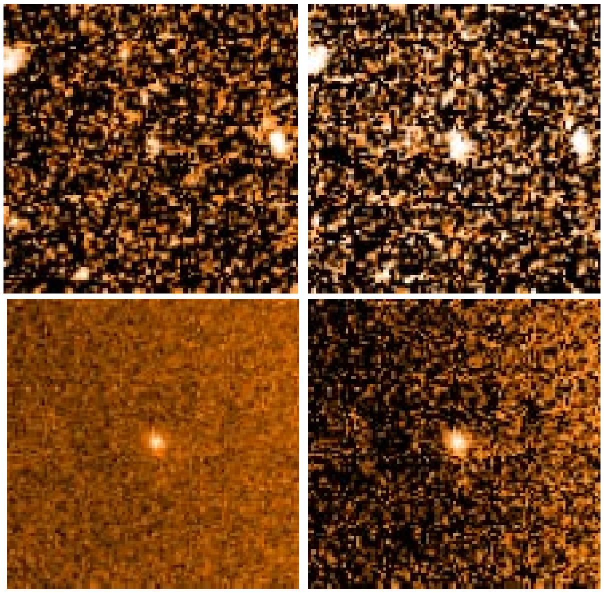

Figure 3. Images at F606W, F814W, J and K' clockwise from top left respectively of CUDSS14A. The images are all co-centred on the extremely red optical source, and are all 10 × 10 arcseconds.

The brightness of CUDSS-14A in F606W, F814W J and K' in apertures of 1, 2 and 4 arcsec diameter are listed in Table 2. The colours are broadly consistent in the different apertures but with a trend to be bluer in larger apertures. This new photometry agrees well with earlier measurements in larger apertures by Lilly et al (1999). Optical spectroscopy was also attempted but no detection was made.

2.3 UKIRT Observations

CUDSS14A was observed with the CGS4 spectrometer on the nights of April 13 and 16 1999 using the 300 mm focal length camera and 40 lines/mm grating. The 2.4 arcsec slit was centred on the radio position, and the observing and data reduction procedures described by Eales and Rawlings (1993) were used. In the K and H bands we observed in first order ($\lambda/\delta\lambda = 400$) for 160 minutes, and in J we observed in second order ($\lambda/\delta\lambda = 800$) for 80 minutes.

Continuum was detected at K, but not at J or H. No spectral lines were seen in any of the bands and we estimate the upper limits on the lines as 1.1×10^{-19} W m^{-2} in the region 2.02-2.3 μm, 1.3×10^{-19} W m^{-2} in the region 1.5-1.8 μm, and 2.8×10^{-19} W m^{-2} in the region 1.1-1.3 μm. To derive these limits we have assumed that a spectral line would have a spectral width equivalent to a velocity dispersion of 200 km s^{-1}. These limits are slightly more conservative than 3σ limits, since we have enough spectral range that we might expect a 3σ fluctuation by chance. The limits have been chosen to be slightly larger than the largest feature in each spectral range.

3 DISCUSSION

3.1 The identification

The IRAM position is 1.4 arcsec from the nominal SCUBA position and is also only 1.2 arcsec from the 5 GHz position of Fomalont et al (1991) and 1.5 arcsec from the optical ID (Lilly et al 1999). Since there is no other candidate in each band than the one we show and all the positions lie easily within their respective 2σ astrometric uncertainties of each other (in fact the IRAM, radio and optical positions are only just outside their respective 1-σ uncertainties) we believe the identification to be extremely robust.

3.2 The Redshift

In Lilly et al (1999) we suggested a redshift in the range z=2-3, based on the rather uncertain optical and infrared colours available at that time. We can now use our new data to provide further photometric constraints.

3.2.1 Radio and Submillimetre

Carilli and Yun (1999; hereafter CY99) suggested that the strong radio-FIR correlation could be used to provide constraints on the redshifts of SCUBA survey sources. The original CY99 relationship is based on a model, but in a follow-up paper (Carilli and Yun 2000, hereafter CY00) they used observational data from 17 galaxies observed in the submillimetre by Lisenfield, Isaak and Hills (1999) to produce an empirical relationship, which tends to result in somewhat lower redshifts than their original one. Both these results have now been superseded however by Dunne et al (2000) who have made a SCUBA survey of 104 nearby galaxies. Using Dunne et al's empirical relationship between 850 μm and 1.4 GHz flux density, including the intrinsic scatter to derive an uncertainty, the measured 1.3 mm to 850 μm spectral index of 3.2 and the 1.4 to 5 GHz radio spectral index of -0.2±0.3, we obtain z∼2.2±0.5 for CUDSS14A. For completeness we note that CY00 would result in z∼2.9±0.7 and CY99 in z∼5.0±1.0. The rough consistency of the CY00 and Dunne et al results and the inconsistency of the CY99 prediction demonstrates both the uncertainty in this technique (see also Blain 1999) but also the manner in which it is rapidly improving.

We can also use the fact that we have upper limits at 450 μm and 2.8 mm to provide further constraints. To do this we take two extreme template spectra, namely the nearby starburst galaxy M82, which has a dust temperature of 48K and is optically thin throughout the FIR and submm region (Hughes et al 1994), and Arp220, which has a fitted dust temperature of 62K and is optically thick shortward of 200 μm (see e.g. Downes, Solomon & Radford 1993).

As demonstrated in Figure 4, CUDSS14A *cannot* be at low redshift, for either template, otherwise we would have detected it at 450 μm. Conversely it is unlikely to be at very high redshift, for either template, otherwise we would have detected it at 2.8 mm. In fact the detections and upper limits constrain the redshift to the range $2 < z < 5$.

It would be possible to allow a lower redshift if the emitting dust were much colder. In order to be consistent with the 1.3 mm detection and 450 μm upper limit however, for

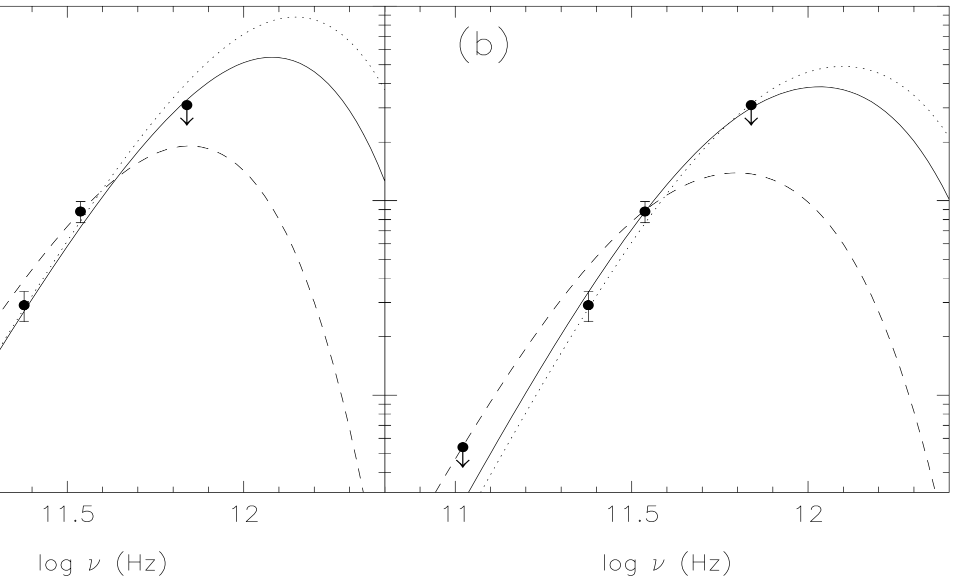

Figure 4. Comparison of the mm/submm spectrum of CUDSS14A with that of (a) M82 and (b) Arp220 at z=2.0 (dots), 2.5 (solid) and 5 (dashed) with arbitrary shifts in absolute flux level. Note that the M82 spectrum is not consistent with the data for z=2.0 but is just consistent for z=5, whereas Arp220 is just consistent at z=2.0 but is not consistent for z=5. Thus for these templates we can constrain the redshift to the range 2.0 to 5.0.

z$\leq$1 the temperature would have to be $\leq$ 20K. Although this would reduce the source luminosity somewhat (depending on the unobserved FIR spectral shape), it also increases the required gas and dust mass to $\geq 10^{11} M_{\odot}$, which is rather excessive. Interestingly, the 450/1300 μm flux constraint for CUDSS14A is identical to that found for HDF850.1 by Downes et al (1999) and they reach the same conclusion, that the source is unlikely to be at such low redshift. We also note that no sources as cold as 20K are known at low redshift and furthermore, that higher luminosity sources also tend to be warmer. Even at the lower end of any possible luminosity range it seems very unlikely to us that such a luminous object would be very cold.

3.2.2 Optical and Infrared

CUDSS14A is an extremely red object (ERO) with $(V-K)_{AB} \sim 6$ corresponding to a Vega-normalized colour of $(V-K) \sim 8$. Other EROs have been identified with SCUBA sources (Smail et al 1999), and Barger, Cowie and Richards (2000) have shown that many very red radio source identifications are detectable with SCUBA. An interesting consequence of the very red colours of a source like CUDSS14A is that such galaxies would rapidly become extremely faint if placed at higher redshifts (Dey et al 1999). This is illustrated in Figure 5 where we show the expected V, I, J and K magnitudes as a function of redshift assuming that the real source is (a) at z=2 and (b) at z=4. In the former case, the source would become very hard to detect at wavelengths below 1μm at redshifts as low as 3. The implications of this are that SCUBA sources for which no optical identification can be found even to extremely faint levels such as reached by the Hubble Deep Field are not neccessarily at very high redshifts, z$\gg$3.

The IJK colours of CUDSS14A are consistent with an Sb galaxy at z=2.5 (as suggested in paper II), however the VIJ colours are also consistent with an Sa galaxy at z=1.5, and the overall spectrum is so extremely red it is not very different from a power law. Therefore we cannot make any firm conclusions based on the colours, but most probably z is less than 4.5 based on the V detection.

If CUDSS14A were at z $\sim$2.2-2.5 then Hα would appear

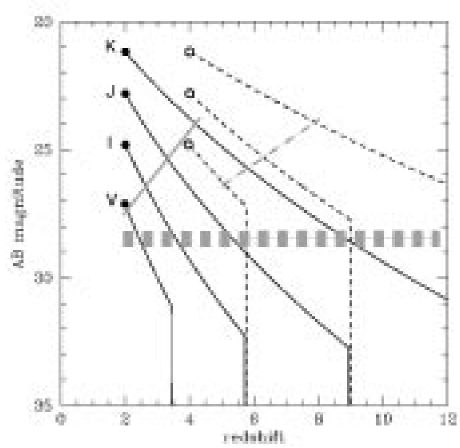

Figure 5. The expected variation of the V, I, J and K magnitudes (in AB) with redshift of a source identical to CUDSS14A derived assuming that CUDSS14A as observed lies at z = 2 (solid lines starting at the solid symbols at z = 2) and at z = 4 (dashed lines starting at the open symbols at z = 4, no V curve is plotted in this case since the Lyman break should suppress V very rapidly above z $\sim$4). The horizontal dashed area in grey represents the approximate magnitude limits of the HDF. The diagonal grey lines represent more typical limits to ground-based imaging and are shown for the two sets of magnitude-redshift predictions. An $\Omega = 1$ Universe has been assumed.

in the range 2.1 to 2.3 μm, and the [OIII] 5007 line would appear at 1.60 to 1.75 μm. No lines are observed. However we note that spectroscopic observations of nearby ULIRGs by Kim, Veilleux and Sanders (1998) imply the lines are suppressed compared to the level expected from the FIR-derived star-formation rates in these objects, and in fact if the ratio of optical/infrared line emission to FIR luminosity in SCUBA-selected galaxies is similar to that found in nearby ULIRGs then 8-10 m telescopes will be required to detect them. Therefore the non-detection of any lines cannot be used to rule out a redshift of 2-3.

The optical/infrared, radio and mm/submm data therefore all argue strongly for a redshift $2.0 < z < 4.5$ with some preference for a redshift around 2.2 to 2.5.

3.3 AGN Heating ?

A source at redshift z>2 with a dust temperature around 50K has a minimum possible source size of 0.1 arcsec to produce an observed flux of 2.9 mJy at 240 GHz, which at z$\sim$2-5 corresponds to roughly $1-2$ kiloparsec, which is the typical size for circumnuclear starburst regions in local ULIRGs. Another way of looking at this is to say that if the emitting region in CUDSS14A *is* a typical circumnuclear star-forming region and it is at z$\sim$2-5, then the submm emission must be quite close to being optically thick.

Applying the same argument to the question of whether the FIR luminosity could be produced by AGN heating, we can say immediately that the submm-emitting dust cannot predominantly be heated *directly* by a central AGN, since in order to be at a temperature of 50K or below, for standard dust properties (e.g. Hildebrand 1983) the grains would have to be $\sim$ 5 kpc from a central AGN of luminosity $4{\times}10^{12}$ L$_\odot$ and would therefore have been resolvable. Conversely if optically thin dust were only 1 kpc from such a central source its temperature would be $\sim$ 200K which is not consistent with the ISO and 450 μm non-detections. However we cannot rule out heating via radiative transfer through a large column of dust, with the observed mm/submm emission arising only close to the outer surface.

The launch of the Chandra and XMM X-ray satellites offer the opportunity to observe AGN emission directly in these sources if it is present and should help to solve this question definitively. Initial Chandra observations presented by Mushotsky et al (2000) suggest that the hard x-ray background has been resolved into heavily obscured active galaxies, for which the SCUBA-selected objects are a plausible counterpart. However the limited data so far available from Chandra on SCUBA sources (Fabian et al 2000) suggest that these are more like starburst galaxies, unless they are Compton-thick and the scattered X-rays are weak or also absorbed.

3.4 Source properties

We can derive a total luminosity for CUDSS14A of $\sim$3-$6{\times}10^{12}$ L$_\odot$ for 2<z<4.5. This luminosity estimate is for an Arp220-like spectrum where the total luminosity is completely dominated by the Submm/FIR. For an M82-like spectrum the total luminosity could in fact be considerably higher. For a standard initial mass function, this luminosity corresponds to an ongoing star-formation rate of $\sim$1000 M$_\odot$ yr^{-1}, which is hard to sustain for a cosmologically significant time, unless the IMF is very heavily biased towards massive stars.

We can also estimate a total gas mass using the techniques laid out in Hildebrand (1983) and Gear (1989) (see also Hughe, Dunlop and Rawlings 1997) to give roughly $\sim 10^{10}$ M$_\odot$. The uncertainty in this estimate is probably at least a factor 5 in each direction however, given the uncertainty in dust temperature, optical depth, grain properties, redshift and cosmology. A galaxy of this mass could only sustain the derived star formation rate for a period of around 10 million years. So these results are all consistent with CUDSS14A being a gas and dust-rich galaxy undergoing a short-lived period of extensive star-formation.

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